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PHOTOEMITTER CHARACTERIZATION: RESPONSE.(U)
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Technical Report 436

PHOTOEMITTER CHARACTERIZATION: RESPONSE

CJ Gabriel

1 June 1979

Interim Report: October 1977 — October 1978

Prepared for
Naval Air Systems Command

NAVAL OCEAN SYSTEMS CENTER
SAN DIEGO, CALIFORNIA 92152

NAVAL OCEAN SYSTEMS CENTER, SAN DIEGO, CA 92152

AN ACTIVITY OF THE NAVAL MATERIAL COMMAND

SL GUILLE, CAPT, USN
Commander

HL BLOOD
Technical Director

ADMINISTRATIVE INFORMATION

The work reported herein was approved by the Naval Air Systems Command and conducted over the period October 1977 to October 1978.

ACKNOWLEDGEMENTS

Discussions with Stephen A Miller, NOSC Code 9223, were very helpful in the generation of this report and are greatly appreciated.

Released by
H. H. Wieder, Head
Electronic Materials Sciences Division

Under authority of
C. D. Pierson, Head
Electronics Engineering
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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: NOSC Technical Report 436 (TR 436)

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle): Photoemitter characterization: Response

5. TYPE OF REPORT & PERIOD COVERED: Interim report, Oct [redacted]77 - Oct [redacted]78

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s): C.J. Gabriel

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS: Naval Ocean Systems Center, San Diego, CA 92152

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 62762N, F54583, ZF54583001, 834-CG13

11. CONTROLLING OFFICE NAME AND ADDRESS: Naval Air Systems Command, Washington, DC 20361

12. REPORT DATE: 1 Jun [redacted]79

13. NUMBER OF PAGES: 27

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report): Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report): Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Measurement techniques for the characterization of photoemitters are developed and described mathematically. Basic assumptions are given and the limitations of the applicability of the methods are discussed.

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INTRODUCTION

PURPOSE

A description of some measurement techniques and instrumentation that are useful for the characterization of the output response of photoemitters to be used in communications is given. Also included is enough background material to provide the formalism for the analysis accompanying each measurement description and, more importantly, to define the term "characterization," including an explicit statement of the basic assumptions, which are often only implied, upon which photoemitter response characterization is presently based.

SCOPE

This report is limited to a general consideration of the output response of photoemitters to input drive signals. The measurement of noise and electrical circuit properties of photoemitters is not discussed, even though these properties must be known in order to characterize a photoemitter. While the measurement techniques and instrumentation that are described can be usefully applied to the characterization of any photoemitter, not all possible measurements required for all possible photoemitters will be considered. The primary restrictions are that the photoemitter be stable and that the parameters that affect or characterize its output be independent of time. In order to simplify further the presentation, it will be assumed that the photoemitter output response is unpolarized and incoherent, and that a finite planar radiating surface can be defined for the photoemitter.

Consideration of the polarization dependence of the coefficients for optical transmission at an interface of typical photoemitter materials, the finite spectral bandwidth, and the useful life-time of photoemitters indicates that these assumptions cannot be precisely true; however, for many photoemitters they are satisfied well enough to justify their application here.

The instrumentation and measurement techniques discussed may have more general applicability; however, only the visible and near-infrared regions of the spectrum will be considered. Also, the discussion will be presented in terms of analog system measurement theory and will be restricted to deterministic waveforms; however, this is not intended to imply that digital measurement techniques and stochastic analysis are not useful tools in the characterization of photoemitter response.

This report is directed implicitly towards the characterization of light emitting diodes (LED's) that are intended to be used with multimode optical waveguides. Consequently, a radiometric, rather than physical optics, approach has been adopted. Because injection lasers may not adequately satisfy the assumptions of lack of polarization and coherence, the application to them of the approach to be discussed must be regarded as yielding a limited, but still useful, characterization.

BACKGROUND

PHOTOEMITTER

For purposes of this report, a photoemitter is a device having an emitting surface that radiates electromagnetic energy in response to an electrical signal applied at the input

terminals of the device. Figure 1 shows a block diagram of such a device. Output radiation is considered to be measured with specified environmental and drive conditions. The emitting surface is generally an arbitrarily chosen plane area through which all of the radiated flux passes.

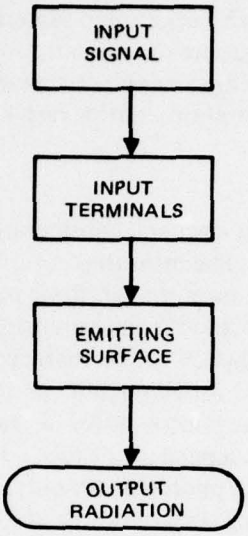

Figure 1. Block diagram of a photoemitter.

Within the scope of this report, a photoemitter can be represented as the functional relationship

$$L(t, p, q) = F[p, q; J(t'), t' \leqslant t] \tag{1}$$

where L(t, p, q) is the output spectral radiance (referred to the direction of propagation) in which t is the observation time; p represents the output parameters λ, $\bar{n}$, and $\bar{r}$ which characterize the radiation and are, respectively, the wavelength (spectral parameter), the direction of propagation, and the position on the emitting surface; and q is all other parameters, such as ambient conditions, bias voltages, and drive circuit properties, that affect the output radiation. The q dependence will be suppressed in expressions in the latter parts of this report. J(t′) is the signal, typically current or potential, at the photoemitter input at all times t′ not greater than t.

RADIOMETRIC QUANTITIES

The spectral radiance is the most microscopic of the quantities commonly used to describe an incoherent radiation field at a point. It is the spectral radiant flux per unit solid angle and per unit area normal to the direction of propagation and has typical units of W $sr^{-1}\ m^{-2}\ nm^{-1}$.

The total radiant flux radiated by the photoemitter is obtained from L(t,p,q) by

$$\Phi(t, q) = \int_p dp\, L(t, p, q) \tag{2}$$

where the integral over the output space means that the output radiation parameters are to be integrated over all possible wavelengths, all possible directions of radiation, and over the area of the emitting surface. The incremental volume element is

$$dp = \bar{n} \cdot \bar{s}\, dS\, d\Omega\, d\lambda \tag{3}$$

where $\bar{s}$ is the unit vector normal to the emitting surface at the point of emergence and dS and $d\Omega$ are the incremental surface and solid angle elements, respectively. Figure 2 shows the geometric quantities for an arbitrary emitting surface. $\Phi(t, q)$ has typical units of watts. The total quantity of radiation emitted within the time interval between t_1 and t_2 is

$$Q(t_1, t_2, q) = \int_{t_1}^{t_2} dt\, \Phi(t, q) \tag{4}$$

$Q(t_1, t_2, q)$ has typical units of joules. Clearly, measurements of either $\Phi(t, q)$ or $Q(t_1, t_2, q)$ are insufficient, in general, to characterize a photoemitter; however, such measurements can be used to establish performance bounds.

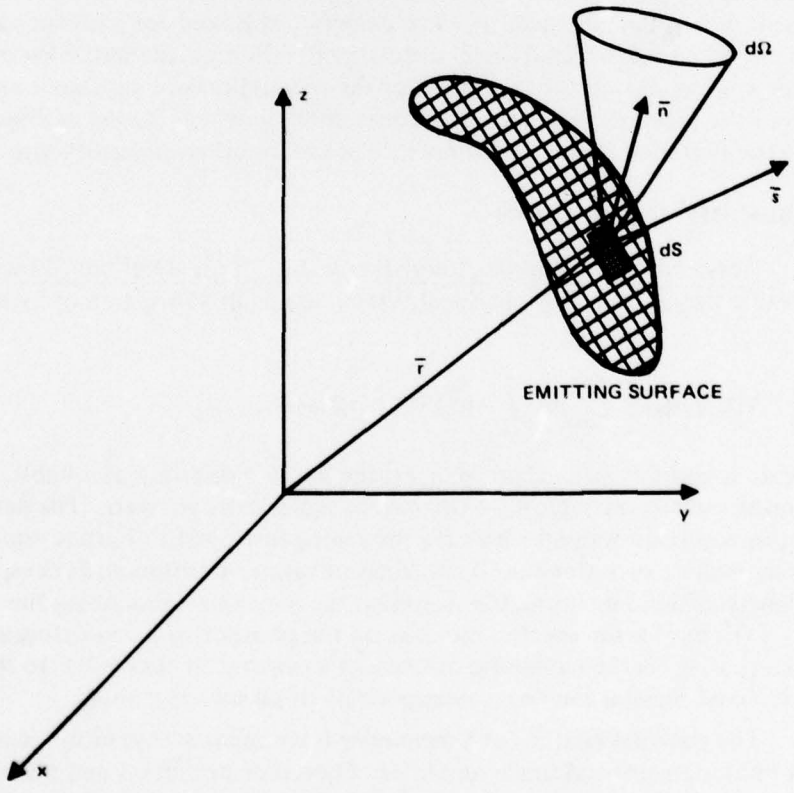

Figure 2. Geometric quantities for an arbitrary emitting surface.

Two other radiometric quantities that are of greater use for the characterization of photoemitters are the spectral radiant emittance, $M(t, \lambda, \bar{r}, q)$, and the spectral radiant intensity, $I(t, \lambda, \bar{n}, q)$. The units of $M(t, \lambda, \bar{r}, q)$ are typically $W \cdot m^{-2} \cdot nm^{-1}$ and those of $I(t, \lambda, \bar{n}, q)$ are typically $W \cdot sr^{-1} \cdot nm^{-1}$. These quantities are related to the spectral radiance through the integrals

$$M(t, \lambda, \bar{r}, q) = \int_{\Omega} d\Omega\, \bar{n} \cdot \bar{s}\, L(t, \lambda, \bar{n}, \bar{r}, q) \tag{5}$$

and

$$I(t, \lambda, \bar{n}, q) = \int_{S} dS\, \bar{n} \cdot \bar{s}\, L(t, \lambda, \bar{n}, \bar{r}, q) \tag{6}$$

In (5), the integration over Ω includes all outward directions from the radiant surface yielding the spectral radiant flux per unit surface area at the point $\bar{r}$ on the emitting surface. In (6) the integration over S includes that part of the radiant surface that is radiating in the direction $\bar{n}$ yielding the spectral radiant flux per unit solid angle in the direction $\bar{n}$.

The integration of either $M(t, \lambda, \bar{r}, q)$ or $I(t, \lambda, \bar{n}, q)$ with respect to $\bar{r}$ over S, or with respect to $\bar{n}$ over Ω, respectively, yields the spectral radiant flux $\Phi(t, \lambda, q)$. The radiant emittance $M(t, \bar{r}, q)$ and the radiant intensity $I(t, \bar{n}, q)$ are obtained by integration of $M(t, \lambda, \bar{r}, q)$ and $I(t, \lambda, \bar{n}, q)$, respectively, over λ. Here the same letter has been used to represent more than one quantity. For example, M is used for both the radiant emittance and the spectral radiant emittance, the distinction being made in the list of arguments. That is, λ is included in the arguments of the spectral radiant emittance and not in the arguments of the radiant emittance. This convention, in which the list of arguments serves to define the function, is used in radiometric as well as other quantities throughout this report.

MEASUREMENT EQUATION

Measurements of the spectral radiance, $L(t, p, q)$, are obtained indirectly from observable signals, generally electrical, $V(t, q, q_S)$ related to $L(t, p, q)$ by an equation of the form

$$V(t, q, q_S) = \int_{-\infty}^{\infty} dt' \int_{p} dp\, L(t', p, q)\, s(t-t', p, q_S) \tag{7}$$

where dp is given by (3) and $s(t, p, q_S)$ is the impulse response of a stable, time-invariant, linear measuring instrument typically expressed in signal units per watt. The parameter q_S represents those quantities upon which the measuring instrument's output response depends, and may include such things as the settings of various positioning devices, the transmission wavelength of a monochromator, as well as the parameters describing the ambient conditions. In (7), $L(t', p, q)$ is the spectral radiance on the photoemitter's radiating surface at time t' and $s(t-t', p, q_S)$ is the measuring instrument's response at time $t \geq t'$ to this spectral radiance. The observed signal is the linear superposition of all such responses.

The essential features of a measuring instrument are typically: collection optics, linear photodetector and linear amplifier. Photodetector arrays and photographic film are sometimes incorporated; however, these seem to be better suited for rapid qualitative results rather than quantitative characterization. Electronic signal processing equipment follows these essential components to generate the desired data.

CHARACTERIZATION MEASUREMENTS

The inversion of (7) to obtain L(t, p), or more precisely, an average of L(t, p) over a small range of the output parameters Δp from the observed signals, V(t) (where the q and q_s dependence has now been suppressed), is facilitated by the proper choice of measuring instrument and much of the subtlety and difficulty of photoemitter characterization is associated with this effort. However, even given L(t, p), the correlation of input signals, J(t), with L(t, p) to obtain the functional relationship expressed by (1) is still a formidable task because of the nonlinear nature of (1). The appendix to this report contains a brief discussion that illustrates that even for a simple form of (1) this task is still complex.

While it would be desirable to characterize photoemitters completely, no practical procedure is presently available for doing this. Instead, the measurement of a few performance characteristics selected for their usefulness in making comparisons between photoemitters, with specific applications in mind, is the best that can be done. The first step in doing this is to select an appropriate set of input signal waveforms, keeping in mind, of course, that because of the nonlinear nature of (1) the amplitude as well as the form is important. A typical set might include quasistatic functions, sinusoidal functions, and step functions.

Now, with this restriction on input signals, the inversion of (7) must be considered. The direct approach to this problem of characterizing a radiation field requires that the measuring instrument be chosen so that it responds only to radiant flux in a narrow spectral band, $\Delta\lambda$, within a small solid angle, $\Delta\Omega$, from a small region, ΔS, of the emitting surface. Under these conditions, (7) reduces to

$$V(t) = \bar{n}_o \cdot \bar{s}\ \Delta\lambda\Delta\Omega\Delta S \int_{-\infty}^{\infty} dt'\ \bar{L}(t', p_o)\, s(t-t', p_o) \tag{8}$$

where $\bar{L}(t, p_o)$ is the spectral radiance averaged over the small volume of radiation parameter space $\Delta\lambda\Delta\Omega\Delta S$ around p_o, where this volume is small enough so that s(t, p) can be considered constant within this volume. If the photodetector and amplifier combination is distortionless over the range of frequencies contained in $\bar{L}(t, p_o)$, not necessarily the same range as contained in J(t), then (8) reduces to

$$V(t) = \bar{n}_o \cdot \bar{s}\ \Delta\lambda\Delta\Omega\Delta S\ \bar{L}(t-\tau, p_o)\, P(p_o) \tag{9}$$

where $P(p_o)$ and τ are, respectively, the response and time delay of the distortionless measuring instrument. Thus, from (9) the $\bar{L}(t, p)$ corresponding to a given J(t) can be obtained to whatever degree of resolution is compatible with the basic assumption of complete incoherence and the sensitivity of the measuring instrument.

One realization of the required electro-optical component of the measuring instrument is illustrated in Figure 3, which shows a calibrated photodetector constrained to move on a sphere in such a way that its responsive surface subtends a small constant solid angle $\Delta\Omega$ from the sphere center, and a photoemitter positioned near the center of the sphere and masked in such a way that only a small area ΔS located at the center of the sphere is able to irradiate the photodetector. Interposed between the photoemitter and photodetector is a narrowband spectral filter with an effective passband of $\Delta\lambda$. If the radius of the sphere is large enough so that the responsive surface of the photodetector receives flux uniformly from each point on the photoemitting surface within ΔS, then the conditions leading to (9)

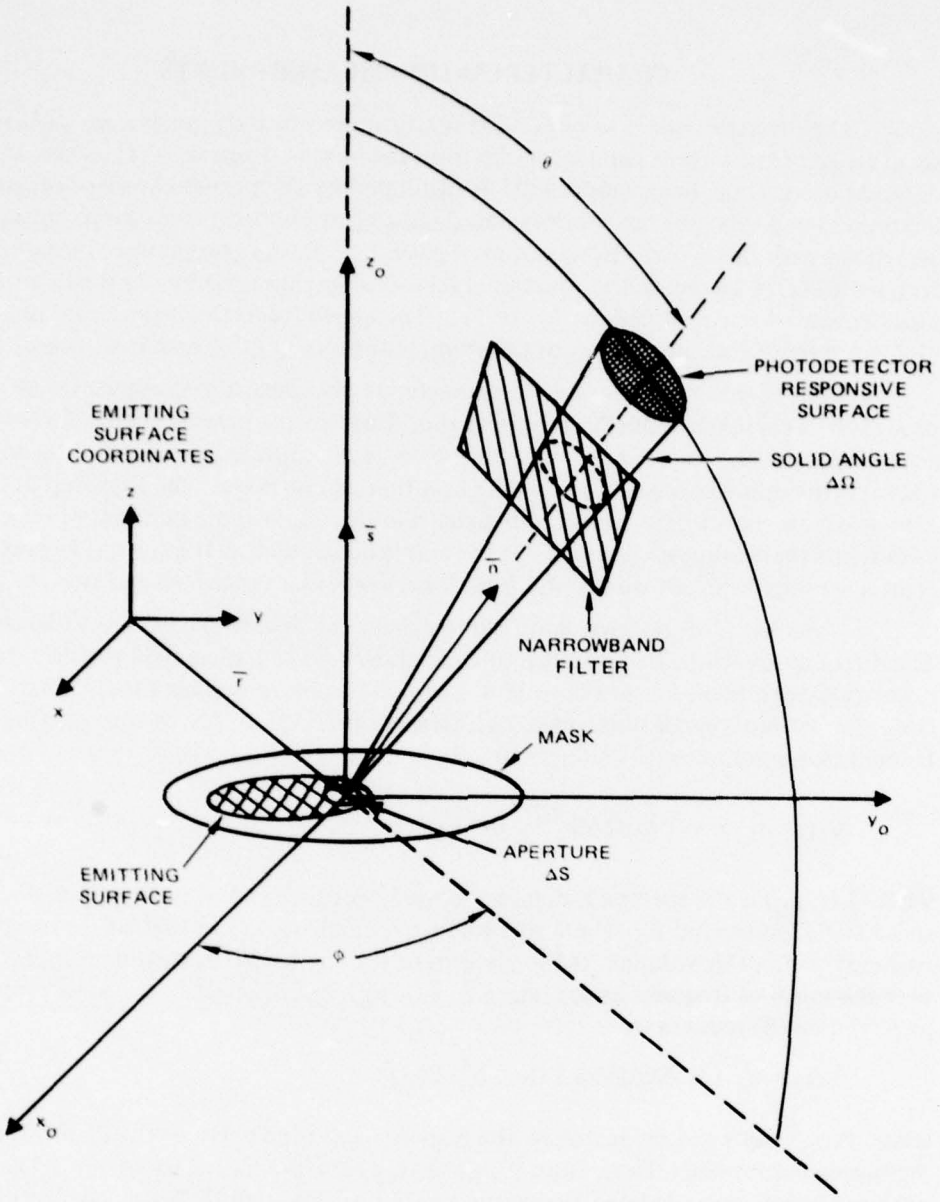

Figure 3. Representation of apparatus for the measurement of spectral radiance.

are satisfied, provided the filter passband is narrow with respect to any variation in the spectral response of the measuring instrument. $P(p_o)$ in (9) is then simply the product of the peak transmittance of the filter, the response of the photodetector to collimated, uniform, monochromatic radiation, and the gain of the amplifier.

The approach described so far, based on (9), suffers from three difficulties that make it unsuitable for routine measurements: (a) because all three of the resolution elements appear as factors, the observed signals can be small, (b) in general, a great amount of data

must be taken and processed, and (c) the set of input signals, J(t), may require large bandwidths of the photodetector and amplifier. All three of these difficulties are overcome by the expediency of reducing, in some specified manner, the resolution in all but one of the parameters; thus, spectral-resolved radiant flux measurements (spectral output), angle-resolved radiant intensity measurements (far-field pattern), spatial-resolved emittance measurements (near-field pattern), and time or frequency-resolved temporal response measurements (rise and fall time or frequency response) are made. Since it is more convenient to make relative rather than absolute radiometric measurements, instruments that are not calibrated radiometrically are used to measure relative distributions and then a single measurement is made with a radiometrically calibrated instrument to provide the gauge for the complete set of measurements. Primarily because of the constraints imposed by conventional optical instruments, the angle-resolved radiant intensity measurement, which does not require the interposing of absorbing or scattering components, other than the atmosphere, between the photoemitter and photodetector, is the most suitable for this purpose.

One aspect of the resulting simplification that warrants explicit mention is that under this measurement plan, only the temporal response measurement needs to be carried out using the full set of selected input waveforms. This means that the other measurements can be made using low-frequency, narrowband measuring instruments, which broadens the choice of the photodetector, simplifies the circuitry, and provides a significant improvement in the signal-to-noise ratio for these measurements.

Often, further reduction in effort is obtained through consideration of the intended application of the photoemitter. For example, in many communication systems the response of the electro-optical component does not depend significantly on the position on the emitting surface of the origin of the radiant flux. Consequently, it is frequently necessary only to consider the characteristics of the total flux passing through certain specified apertures rather than characterizing the device completely.

CHARACTERIZATION INTERPRETATION

The tacit assumption made in choosing the radiant power, specifically the spectral radiance, to characterize the optical output of an incoherent photoemitter is that a significant portion of optical communication systems can be discussed in terms of the transfer of spectral radiance through the propagating medium. Of course, not all systems can be treated this way and in general a more complete description in terms of the amplitude and phase of the electromagnetic field at the input to the system would be necessary. However, except for the most extreme cases, useful estimates of the flux transmitted to the receiver can still be made from only a knowledge of the spectral radiance at the output of the photoemitter and the details of the propagating medium.

The question remains, however. In which situations will this rather limited set of characterization measurements be sufficient to permit an adequate description of the spectral radiance to be obtained? If the spectral radiance, which has a general form (1), can be factored into the separated form

$$L(t, \lambda, \bar{n}, \bar{r}) = \Lambda(\lambda)\, \theta(\bar{n})\, X(\bar{r})\, f[J(t'), t' \leqslant t] \qquad (10)$$

where the spectral, angular, spatial, and time responses are independent, then the spectral radiance can be expressed in terms of the four relative measurements and the single absolute measurement. The four relative measurements will yield

$$L(t, \lambda, \bar{n}, \bar{r}) \propto m_1(\lambda)\, m_2(\bar{n})\, m_3(\bar{r})\, m_4(t) \tag{11}$$

where $m_1(\lambda)$, $m_2(\bar{n})$ and $m_3(\bar{r})$ are, respectively, the relative measurements of the spectral, angular, and spatial responses measured with arbitrary input signals, and $m_4(t)$ is the relative measurement of temporal response measured with the input signal waveform for which it is desired to obtain the spectral radiance. The proportionality constant will depend on the normalization chosen for the relative measurements and on the details of the particular absolute measurement used.

NORMALIZATION

One convenient normalization is in terms of Φ, the total radiant flux emitted with a constant input signal; in this case

$$L(t, \lambda, \bar{n}, \bar{r}) = \Phi \frac{m_1(\lambda)\, m_2(\bar{n})\, m_3(\bar{r})\, m_4(t)}{\int d\lambda\, m_1(\lambda) \int d\Omega\, \bar{n} \cdot \bar{s}\, m_2(\bar{n}) \int dS\, m_3(\bar{r})\, m_4} \tag{12}$$

where m_4 is the waveform response, $m_4(t)$, obtained for constant input signal. If the relative measurements are normalized so that

$$\int d\lambda\, m_1(\lambda) \triangleq 1 \tag{13}$$

$$\int d\Omega\, \bar{n} \cdot \bar{s}\, m_2(\bar{r}) \triangleq 1 \tag{14}$$

$$\int dS\, m_3(\bar{r}) \triangleq 1 \tag{15}$$

$$m_4 \triangleq 1 \tag{16}$$

then the proportionality constant for (11) is Φ. If instead of (14) the normalization

$$m_2(\bar{s}) \triangleq 1 \tag{17}$$

is chosen, then the proportionality constant for (11) is $I(\bar{s})$, the radiant intensity normal to the photoemitting surface measured at constant input signal. If (14) and (15) are modified to be integrals over a restricted radiation cone and a restricted emitting area, respectively, such as might be defined by an optical fiber at the emitting surface, then the proportionality constant for (11) is the flux within this restricted cone emitted from this restricted area.

EFFECTIVE RADIANCE

If $L(t, \lambda, \bar{n}, \bar{r})$ is not separable, as in (1), then this limited set of measurements will not, in general, yield $L(t, \lambda, \bar{n}, \bar{r})$. They can, of course, still be carried out; however, the results one obtains may depend on the details of the apparatus used. Nevertheless, with some care, consistent measurements can be made, and useful engineering parameters can be derived from them, such as the optical output power through an optical aperture, the output power within an acceptance cone, the wavelength of peak spectral emittance, and the spectral bandwidth.

For this purpose an effective spectral radiance is defined for a specified input waveform according to (12) or some other similar relationship. The choice depends on the intended application. Since (10) is not satisfied, the results that are obtained will depend on this choice. This procedure can result in significant errors if the flux being calculated is radiated from restricted areas into narrow cones, or if the input waveforms used for the measurements deviate greatly from the specified input waveform. These errors can be minimized if the normalization of (11) is chosen so that the proportionality constant reflects the intended use of the photoemitter. For example, if the application is critically dependent on the on-axis flux, the on-axis radiant intensity would be an appropriate choice.

SPECTRAL MEASUREMENTS

The essential element in a measuring instrument intended for spectral measurements is a device for limiting the spectral content of the radiant flux incident on the photodetector to a narrow spectral band. A set of narrowband filters is convenient to use for broadband photoemitters; however, a monochromator is generally required for narrowband photoemitters. This measurement determines the spectral distribution of the photoemitter relative to the spectral distribution of a reference source. If the photoemitter has a narrow spectral distribution, it is only necessary to know that the reference source has a relatively flat spectral output over the appropriate spectral range, rather than the precise spectral distribution of the reference source. Uncalibrated tungsten filament lamps are convenient to use in this situation. If the spectral distribution of the photoemitter is broad, then a spectrally calibrated source, such as a standard lamp, must be used as the reference source.

The general form into which (7) must be cast if a spectral measurement is to have a simple, unambiguous interpretation is

$$V(t) = K(t)\, \Lambda(\lambda_m) \int d\lambda\, T(\lambda, \lambda_m) \tag{18}$$

where $K(t)$ is independent of the monochromator setting, λ_m, and contains implicitly the integrals other than spectral in (7); $\Lambda(\lambda)$ is a spectral distribution that is characteristic of only the photoemitter; and $T(\lambda, \lambda_m)$ is the spectral distribution that is characteristic of the photodetector, monochromator, and collecting optics at setting λ_m. If the relative λ_m dependence of the integral in (18) is known to be the same as that obtained with previous spectral measurements made on the reference source, or if it is nearly independent of λ_m over the spectral range of the photoemitter, then $\Lambda(\lambda_m)$ can be determined to within a multiplicative constant.

The conditions under which (18) is obtained require further consideration. Clearly the simplest situation occurs when the separability condition

$$L(t, \lambda, \bar{n}, \bar{r}) = L(t, \bar{n}, \bar{r})\, \Lambda(\lambda) \tag{19}$$

is satisfied, as would occur if (10) were true. In this case, the instrument response only needs to satisfy the condition

$$s(t, \lambda, \bar{n}, \bar{r}) = s(t, \bar{n}, \bar{r})\, T(\lambda, \lambda_m) \tag{20}$$

Then (7) reduces to the form (18), provided that $T(\lambda, \lambda_m)$ is narrow compared to $\Lambda(\lambda)$. The assumptions (19) and (20) state that the radiant flux emitted from each point in any direction

must have the same spectral distribution and that the measuring instrument's spectral response to this radiation must depend only on the particular monochromator setting. While one can expect to satisfy (20) adequately through the use of a photodetector having separable spectral responsivity and the proper selection and adjustment of the monochromator, the assumption of spectral purity, (19), places a severe restriction on the photoemitter. Indeed, tungsten lamps with coiled filaments do not satisfy (19), since the observed spectral distribution from the filament itself differs from that observed from the regions between the filament coils.

In order to mitigate the ambiguity that can arise in the measurement if (19) is not satisfied, the instrument should be designed so that its response is independent of both $\bar{n}$ and $\bar{r}$. In this case requirement (20) is reduced to

$$s(t, \lambda, \bar{n}, \bar{r}) = s(t)\, T(\lambda, \lambda_m) \tag{21}$$

and the spectral flux radiated by the photoemitter must merely satisfy the less restrictive condition

$$\Phi(t, \lambda) = \Phi(t)\, \Lambda(\lambda) \tag{22}$$

which states that the relative spectral dependence of the flux is independent of the input signal waveform.

It is not difficult to construct an instrument that accurately satisfies (21) by using an integrating sphere at the input to the monochromator; however, the reduction in output signal resulting from the optical mismatch typically occurring between an integrating sphere an a monochromator makes this configuration impractical for routine measurements. Instead, (21) is approximately satisfied for only the flux within the acceptance cone of the monochromator by choosing a photodetector that is, as closely as possible, uniform and isotropic in its response, and the reference lamp is accommodated separately through the use of a Lambert reflector.

In order to simplify the spectral measurement procedure, rather than working with the complete waveform V(t), a functional of V(t) such as the amplitude of some frequency component contained in V(t) is used. Typically, an appropriately biased periodic input signal drives the photoemitter and the measuring instrument displays the RMS value of the fundamental component of V(t).

Even though the condition (22) is less restrictive than (19), the complicated nature of (1) generally results in (22) being only approximately satisfied, so that the measured spectral output can be significantly dependent on the input signal and may depend, as well, on the particular functional of the output signal that has been chosen for the measurement.

SPECTRAL DISTRIBUTION MEASURING INSTRUMENTATION

Figure 4 is a block diagram of a typical apparatus for the measurement of the spectral distribution of the radiant flux from a photoemitter. Incorporated in this apparatus is a flip-mirror so that a convenient and rapid comparison between the reference lamp and the photoemitter can be made.

It is not always possible, because of optical layout constraints, to use a flip-mirror. In such cases, kinematic mounts should be provided for both the reference lamp and the

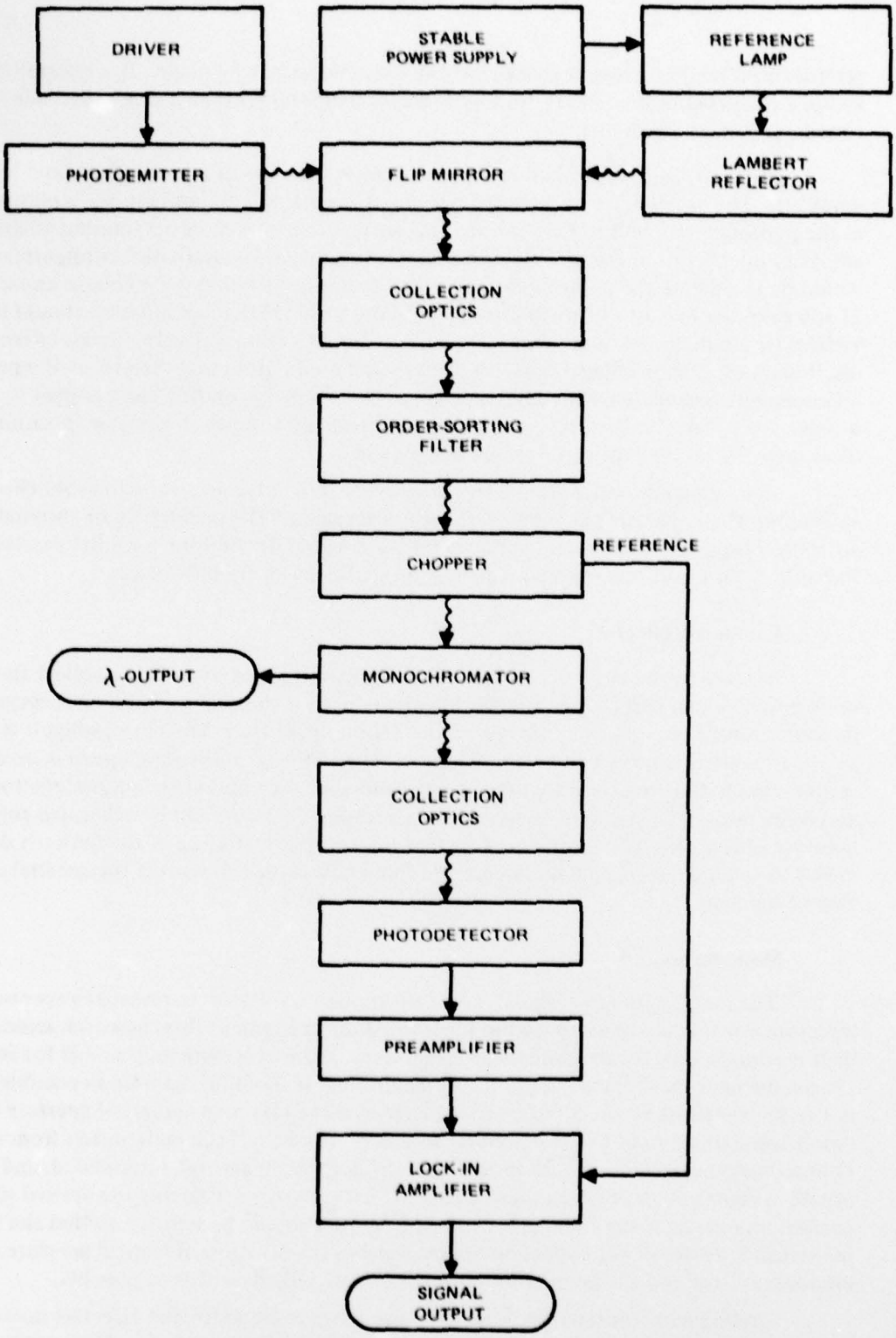

Figure 4. Block diagram of typical apparatus for the measurement of the spectral distribution.

photoemitter so that a rapid exchange of the two sources can be made. It is generally necessary to use a stabilized power supply for the reference lamp, rather than a simple variable transformer, to reduce signal drift.

The electronics illustrated in Figure 4 indicate the use of a preamplifier and lock-in amplifier. The preamplifier is included because it is generally desirable to use a photodiode as the photodetector and to have it operating as a current source into a transimpedance preamplifier in order to obtain the greatest possible linearity. An alternative configuration would be to operate the photodiode with suitable reverse bias and use a voltage amplifier. In any case, the linearity of the photodetector and preamplifier combination should be verified by auxiliary measurements. The lock-in amplifier conveniently provides desirable discrimination against background flux; however, a modulator must then be used when measurements are made on the reference lamp. An ordinary rotating disc chopper is suitable since it has no spectral dependence and it can be stopped in the open position while measurements on the photoemitter are being made.

The collection optics should be constructed using no lenses so as to avoid chromatic aberration when operating in the infrared spectral region. The occurrence of chromatic aberration produces an apparent variation of the spectral distribution with the position of the source. In the visible spectral region, achromatic lenses are satisfactory.

Lambert Reflector

Because of the large size of the standard lamp, it is not practical to collect flux uniformly from all parts of the standard lamp and pass it through the monochromator with the same collection optics as used with a smaller photoemitter. Therefore, when it is necessary to use a standard lamp, a Lambert reflector or, alternatively, a diffusing screen is used in conjunction with it to assure that the spectral radiance it creates at the photodetector is spectrally pure. The standard lamp and the scattering device should be calibrated together; however, this is generally impractical, so that the spectral scattering of the device is determined through auxiliary measurements and this result is used to correct the spectral calibration of the lamp.

Monochromator

The monochromator should have high enough resolution to reveal any spectral structure one might expect to find in the photoemitter's radiant flux; however, excessively high resolution only results in reduced signal levels and is therefore undesirable for routine measurements. Ideally, the slits of the monochromator should be as wide as possible so as not to be overfilled by the photoemitter image, and the effective numerical aperture of the monochromator should be large in order to accept as much of the radiant flux from the photoemitter as possible. These three requirements, are, in general, interrelated, and usually a compromise between maximizing the latter two and attaining the desired spectral resolution must be made. The input collection optics should be selected so that the effective numerical aperture of the collection optics matches the effective numerical aperture of the monochromator and the monochromator slits are overfilled as little as possible.

Grating monochromators generally have a larger slit width and effective numerical aperture for a given spectral resolution than do prism monochromators. This, combined

with the possibility of a convenient linear wavelength scan drive and the wide selection of blaze wavelengths, makes grating instruments the usual choice for this application. Order-sorting filters to eliminate the higher orders must, of course, be used when sources having a broad spectral distribution covering an octave or more are being measured.

Photodetector

For routine measurements whose accuracy is not limited by the amplifier noise or for spectral regions where there are no suitable photomultipliers, the most suitable type of photodetector is the semiconductor photodiode. Since the input signal, J(t), is chosen to be a low-frequency periodic waveform, this type of photodetector can be operated conveniently without reverse bias in the photoconductive mode for this application. Whenever possible the photodetector should be selected to have a spectral response that, in addition to being separable, complements the monochromator so that the combined spectral response is as nearly flat as possible in the spectral range of the photoemitter. In order to produce a desired spectral response, photodiodes are manufactured of several semiconductor materials, including Si, Ge, and various III-V semiconductor alloys. While there is ample information available indicating under which operating conditions silicon photodiodes are linear, such information pertaining to other materials is not readily found. Thus, the linearity of the photodiode should be checked in its intended operating condition, that is, with the bias voltage and preamplifier that are intended to be used.

RADIANT INTENSITY MEASUREMENTS

The essential feature of an instrument for measuring the angular distribution of the radiant intensity is a device for selecting radiation emitted from the photoemitter in a small solid angle about a specified direction. Because of the small size of the photoemitters under consideration, the simplest form of such an apparatus consists of an orthogonal two-axis goniometer, on which the photoemitter can be mounted, and a photodetector placed some distance from the photoemitter in such a manner as to collect only the desired radiation.

In order to make an unambiguous measurement of the angular dependence of the radiant intensity of the photoemitter, (7) must be of the form

$$V(t) = K(t)\,\theta(\bar{n}_g) \tag{23}$$

Where $\theta(\bar{n})$ is the desired angular distribution that is characteristic of only the photoemitter, $\bar{n}_g$ is a direction determined by the goniometer setting, and K(t) is a quantity that is independent of $\bar{n}_g$ and contains implicitly the integrals in (7). The response function of the simple measurement instrument described above will be of the form

$$s(t, \lambda, \bar{n}, \bar{r}) = s(t, \lambda)\, T(\bar{n}, \bar{n}_g) \tag{24}$$

where $T(\bar{n}, \bar{n}_g)$ is the angular response of the instrument for a goniometer setting of $\bar{n}_g$ and has a shape that is independent of $\bar{n}_g$ and significant values only for directions of $\bar{n}$ near $\bar{n}_g$, provided that the photodetector is placed far enough from the photoemitter so that each point of the photodetector views every point of the photoemitter equally well. For an instrument response function of the form (24) the measurement equation (7) will be of the form (23) if the spectral radiant intensity of the photoemitter is of the form

$$I(t, \lambda, \bar{n}) = \Phi(t, \lambda)\, \theta(\bar{n}) \tag{25}$$

as would occur if (10) were true. Condition (25) states that the relative angular distribution of the spectral radiant intensity is independent of wavelength and input waveform.

Condition (25) on the photoemitter can be relaxed somewhat if a photodetector with a flat spectral response over the spectral range of the photoemitter is available. For this situation, (25) is replaced by the condition that the radiant intensity is of the form

$$I(t, \bar{n}) = \Phi(t)\, \theta(\bar{n}) \tag{26}$$

which only requires that the relative angular distribution of the radiant intensity be independent of the input waveform.

Since (26) is not satisfied in general, nor is a photodetector with a flat spectral response always available, there remains some ambiguity in the measured angular dependence because of the freedom in the choice of input waveform and photodetector.

As in the spectral measurement, in order to simplify the procedure, it is typical to use an appropriately biased periodic input signal and display the RMS value of the fundamental component of V(t). The measured angular dependence can depend on the particular functional of V(t) chosen for the measurement if (25) is not satisfied.

ANGULAR DISTRIBUTION MEASURING INSTRUMENTATION

Figure 5 is a block diagram of a typical apparatus for the measurement of the angular distribution of the photoemitter output radiation. The preamplifier and the operating conditions of the photodetector should be selected to provide a linear response. The lock-in amplifier provides desirable discrimination against background flux. Other than local flatness of its spectral response and linearity, no special requirements are placed on the photodetector; however, care should be exercised to prevent radiation from the photoemitter from reaching the photodetector by any path other than the direct one. The goniometer should be provided with sending units so that the emitter orientation can be recorded simultaneously with the photodetector signal.

RADIANT FLUX

The radiant flux in the far field within a given cone is an engineering parameter that is useful for estimating the optical coupling of a photoemitter to a fiber-optic cable. This quantity can be obtained by numerical integration from a measurement of $I(t, \bar{n})$ as indicated by the combination of (6) and (2).

With the addition of a calibration measurement at a single orientation of the goniometer, the relative measurement of angular distribution can be converted to a measurement of $I(t, \bar{n})$ and the numerical integration of the resulting angular distribution then produces the desired engineering parameter. Since, at the present time, photodetectors are calibrated under constant flux irradiation, the calibration measurement must be made dc, without the aid of the reduction of the background provided by the use of the lock-in amplifier, and yields the flux distribution under dc operation. Thus, the signal-to-noise ratio of this measurement might be poor; however, because of the systematic errors involved in the calibration of a photodetector, it is usually adequate. Under the assumption that the relative angular

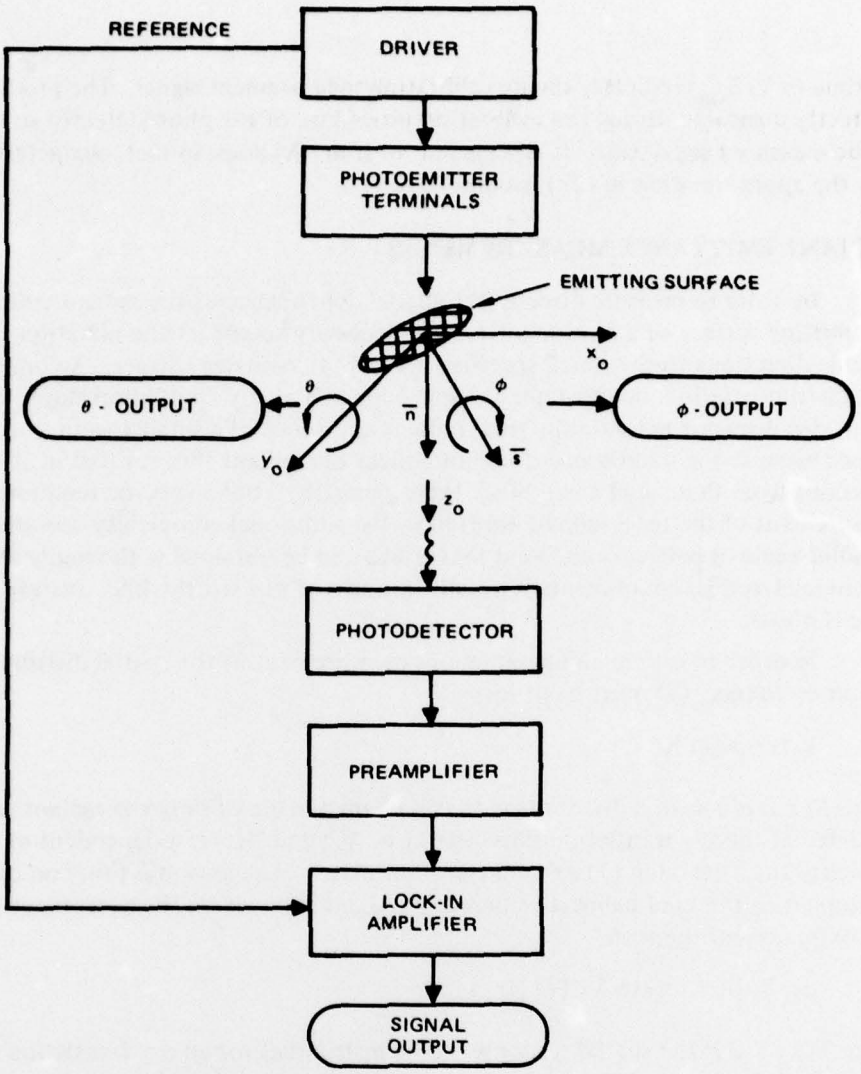

Figure 5. Block diagram of typical apparatus for the measurement of the angular distribution.

distribution $\theta(\bar{n})/\theta(\bar{n}_o)$, where $\bar{n}_o$ is a reference direction, does not vary with the modulation frequency for low frequencies, (23) yields for the dc radiant intensity

$$I(\bar{n}_g) \cong \left[\frac{m_2(\bar{n}_g)}{m_2(\bar{n}_{og})}\right] \frac{V(\bar{n}_{og})\, d^2 \int d\lambda\, m_1(\lambda)}{A \int d\lambda\, R(\lambda)\, m_1(\lambda)} \tag{27}$$

where $m_1(\lambda)$ is the measured relative spectral distribution, $m_2(\bar{n}_g)$ is the measured relative angular distribution, $\bar{n}_{og}$ is the goniometer orientation for the calibration measurement, d is the distance between the photoemitter and the photodetector, $R(\lambda)$ is the dc spectral responsivity of the photodetector to uniform, collimated flux at normal incidence in signal units per watt, and A is the responsive area of the photodetector. The suppression of

the time in $V(\bar{n}_{og})$ indicates the dc calibration measurement signal. The product $R(\lambda)A$ is directly measured during the calibration procedure of the photodetector so that A need not be measured separately. If $R(\lambda)$ is flat, or if $m_1(\lambda)$ does, in fact, characterize $I(t, \lambda, \bar{n})$ then the approximation in (27) becomes exact.

RADIANT EMITTANCE MEASUREMENTS

In order to measure directly the spatial dependence of the radiant emittance of the emitting surface of a photoemitter, it is necessary to collect the radiation emitted in all possible directions from a small specified area of the emitting surface. A common form of such instrumentation incorporates a microscope and an x-y translation stage. Strictly speaking, this device does not measure the total radiant emittance of a small area on the emitting surface because the microscope does not collect the radiant flux emitted in all possible directions from that small area. Since there generally is not a specific requirement for the measurement of the total radiant emittance, the additional complexity required to increase the solid angle of collection beyond that which can be obtained with readily available commercial optical components is usually considered not worthwhile. Instead, the collection angle is noted.

In order to obtain an unambiguous measurement of the spatial distribution of the radiant emittance, (7) must be of form

$$V(t) = K(t)\, X(\bar{r}_\tau) \tag{28}$$

where $X(\bar{r}_\tau)$ is a spatial distribution that is characteristic of only the radiant emittance evaluated at the x-y translation stage setting of $\bar{r}_\tau$, and K(t) is independent of $\bar{r}_\tau$ and contains implicitly the integral in (7) over all the coordinates. The response function of a measurement instrument of the kind being considered to radiant flux within the acceptance cone will be approximately of the form

$$s(t, \lambda, \bar{n}, \bar{r}) = s(t, \lambda)\, T(\bar{r}, \bar{r}_\tau) \tag{29}$$

where $T(\bar{r}, \bar{r}_\tau)$ is the spatial response of the instrument for an x-y translation stage setting of $\bar{r}_\tau$. $T(\bar{r}, \bar{r}_\tau)$ has a shape that is independent of $\bar{r}_\tau$ and significant values only for positions $\bar{r}$ near $\bar{r}_\tau$. Expression (29) is based on the assumption that the photodetector is placed at an image of the emitting surface that is magnified to the extent that the radiant flux incident on the photodetector is essentially uniform and collimated. An instrument response function of the form (29) will yield a measurement equation of the form (28) if the spectral radiant emittance is of the form

$$M(t, \lambda, \bar{r}) = \Phi(t, \lambda)\, X(\bar{r}) \tag{30}$$

Here the fact that the simple measuring instrument under consideration does not collect the radiant flux emitted in all possible directions from the emitting surface has been ignored. Condition (30) states that the spectral radiant emittance has the same relative spatial dependence for all emitted wavelengths and input waveforms. This condition on the photoemitter can be relaxed somewhat if a photodetector that is spectrally flat over the spectral range of the photoemitter is used. Then, (30) is replaced by the less restrictive condition

$$M(t, \bar{r}) = \Phi(t)\, X\, (\bar{r}) \qquad (31)$$

that only requires that the spatial distribution of the radiant emittance be independent of the input waveform. If (31) is not satisfied then the measured spatial dependence can be ambiguous even if a spectrally flat photodetector is used.

As in the spectral and angular measurements, the measurement procedure is generally simplified by using an appropriately biased periodic input signal, J(t), and displaying the RMS value of the fundamental component of V(t); again, the measured spatial dependence can depend on this choice if (30) is not satisfied.

SPATIAL DISTRIBUTION INSTRUMENTATION

Figure 6 is a block diagram of typical apparatus for the measurement of the position distribution of the radiation emitted from the photoemitting surface. The preamplifier and the operating conditions of the photodiode should be selected to provide a linear response. The lock-in amplifier provides the needed discrimination against background flux. Other than local flatness of the spectral response and linearity, no special requirements are placed on the photodiode. The microscope should have objectives that cover a suitable range of numerical apertures so that the effect of the reduced solid angle of collection can be estimated. The x-y translation stage should be provided with sending units so that the emitter position can be recorded simultaneously with the photodetector signal. Another configuration for this instrumentation is one in which the photodetector, which has been suitably masked, is mounted on the x-y translation stage and scanned over the enlarged image of the photoemitter provided by the microscope.

TEMPORAL RESPONSE MEASUREMENTS

In order to generate useful engineering parameters, it is necessary to make temporal response measurements using input signal waveforms that are similar in shape and magnitude to the waveforms that the photoemitter will experience in actual use. To this end, pulse and step responses are frequently determined for photoemitters that are to be used in pulse-code modulated systems, and sinusoidal response is often determined for those that are to be used in analog systems. The results obtained with these waveforms are usually given as rise and fall times and the small-signal 3-dB roll-off frequency, respectively. When more complete information is desired, these waveform selections are sometimes extended to include the response to pseudo-random pulse sequences and linear combinations of sinusoids of differing frequencies from which eye-diagrams and intermodulation distortion are determined.

The essential feature of an instrument for making an unambiguous measurement of the temporal response is a photodetector that has a time response that is separable from its spectral, angular, and spatial responses. In addition, to simplify the interpretation, the photodetector and the amplifier used in conjunction with it must be distortionless over the frequency range of interest. Thus

$$s(t, \lambda, \bar{n}, \bar{r}) = \delta(t-\tau)\, s(\lambda, \bar{n}, \bar{r}) \qquad (32)$$

where $\delta(t-\tau)$ is a Dirac delta function. The response, (32), produces a replica of the input to the measurement instrument delayed by time τ.

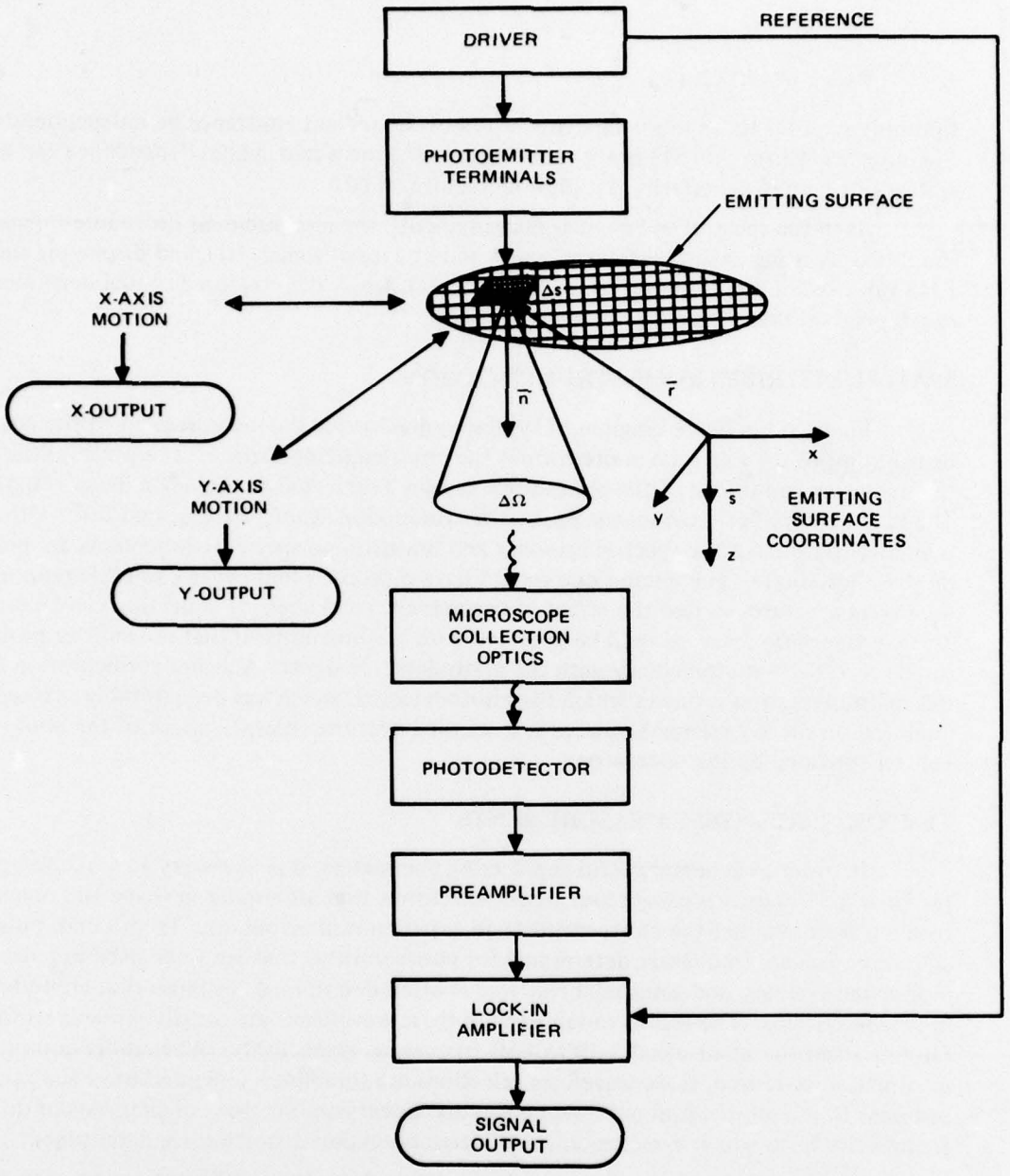

Figure 6. Block diagram of typical apparatus for the measurement of the spatial distribution.

If the spectral radiance is separable in time, that is, if

$$L(t, \lambda, \bar{n}, \bar{r}) = f(t)\, L(\lambda, \bar{n}, \bar{r}) \tag{33}$$

where f(t) characterizes the temporal response, then the observed output signal will be of the desired form

$$V(t) = Kf(t-\tau) \tag{34}$$

where K is independent of time and contains implicitly all of the integrals in (7) other than the time integral. If τ is not known, f(t) can be measured only to within an arbitrary delay.

If the response function of the measuring instrument is not distortionless, then (7) does not reduce to (34), and $f(t-\tau)$ must be obtained by deconvolution from the response function of the instrument, which must be known in detail to carry out such a procedure. Sometimes it is adequate to assume that the instrument has an RC-circuit response for the purpose of estimating engineering parameters.

If (33) is not satisfied, then the measured time response does not have an unambiguous interpretation. In those cases where the effects of this ambiguity are important, it is necessary to select the photodetector so that (33) is reduced as nearly as possible to the form

$$s(t, \lambda, \bar{n}, \bar{r}) = \delta(t-\tau)\, s(\lambda) \tag{35}$$

where now the instrument response is isotropic and uniform. With such an instrument response it is only necessary that the spectral radiant flux be of the form

$$\Phi(t, \lambda) = f(t)\, \Phi(\lambda) \tag{36}$$

in order that the output signal will be of the form of (35). If, in addition to (35), the spectral response of the photodetector is also flat over the spectrum of interest, then the time dependence of the output radiant flux is measured with no separability requirement.

Temporal Response Measurement Instrumentation

The measurement instrumentation is conveniently considered in three parts: (a) the photoemitter driving circuitry and display circuitry, (b) the photodetector and wideband preamplifier, and (c) the optical components for coupling the photoemitter to the photodetector. Figure 7 is a block diagram of instrumentation for the measurement of temporal response.

Electronic Circuity

The requirements on the electronic circuitry depend upon whether pulse response or frequency response is being measured. In the case of pulse response, drive circuits incorporating a charged transmission line and a high-speed switch for discharging it are often used. A low-noise wideband amplifier and sampling oscilloscope or box car integrator are usually used to display the output signal. In the case of frequency response, a swept signal generator and tracking narrowband amplifier are used with a storage oscilloscope or x-y recorder to display the output signal.

The drive circuitry is complicated, somewhat, by the low input impedance of an ohm or so possessed by many photoemitters, which, thus, require a current drive source and some means of accurately monitoring the waveform of the input current that is actually passing through the photoemitter.

Photodetector

The photodetector must be linear over the range of input flux and distortionless over the modulation bandwidth of interest. This bandwidth can be large, so that a high-speed photodetector is required. Such detectors are housed in low-reactance packages, and care

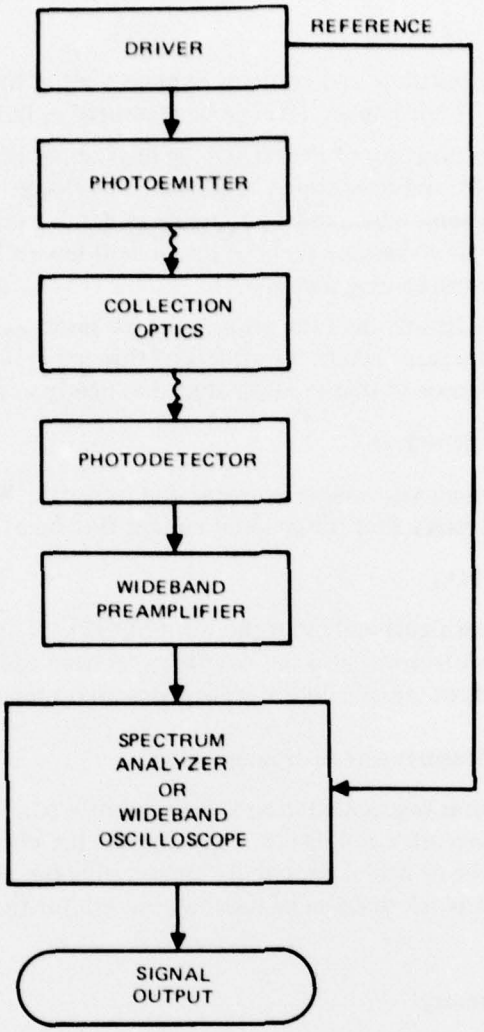

Figure 7. Block diagram of typical apparatus for the measurement of the temporal response.

must be exercised in the design and construction of the network that couples the detector to the preamplifier so as not to compromise the bandwidth. The coupling network must also provide for the application of the proper bias potential to assure the achievement of the full bandwidth.

In addition to the primary requirements of being high-speed and time separable, it is desirable that the photodetector be uniform, isotropic, and locally spectrally flat in its response so as to reduce any possible ambiguity in the measurement. However, these requirements should not be met at the cost of speed of response.

Outside of the visible and near-infrared spectral regions, where photomultipliers are useful, two general types of photodetectors are used: the PIN semiconductor diode, and the avalanche semiconductor diode. The former, being more readily available and simpler to use, is used most often; however, the latter is invaluable when low-noise gain is necessary to obtain an acceptable signal-to-noise ratio.

Optical Coupling

The optical coupling serves two purposes, the concentration of the output flux on the photodetector to enhance the signal-to-noise ratio and the isolation of the drive circuitry from the receiver circuitry to prevent the degradation of the signal-to-noise ratio by the direct pickup of the driving signals. Because of the versatility in the selection of the image spot size possessed by lens or mirror optics, such systems are generally chosen over fiber-optic coupling. The quality of the image produced by the coupling system must be good because of the rather small area of the responsive surface of many high-speed photodetectors.

APPENDIX

One of the simpler general functional representations of a nonlinear photoemitter is

$$L[p, q; J(t'), t' \leq t] = \sum_{n=1}^{P} L_n(t, p, q) \tag{A-1}$$

where

$$L_n(t, p, q) = \int_0^\infty dt_1 \int_0^\infty dt_2 \ldots \int_0^\infty dt_n \, h_n(t_1, t_2, \ldots t_n, p, q)$$

$$\times J(t-t_1)\, J(t-t_2) \ldots J(t-t_n) \tag{A-2}$$

and $h_n(t_1, t_2, \ldots t_n, p, q) = 0$ *if any* $t_i < 0$. *This form is known as a Volterra polynomial* system. If P must be infinitely large in order to represent the photoemitter adequately, then the system is known as a Volterra series system. A value of P=1 describes a linear system.

In most instances, a restriction of the magnitude of the input signal J(t) permits the development of a suitable representation of the photoemitter to be obtained with small values for P. The means of measuring the resulting P Volterra kernels $h_n(t_1, t_2, \ldots t_n, p, q)$, fall into three classes: (a) those using sinusoidal inputs, (b) those using impulse or step inputs, and (c) those using stochastic inputs. As a rule of thumb, as many as $\sum_{n=1}^{P} (2^n - n)$ measurements are required to obtain the P kernels for a single set of times $t_1, t_2, \ldots t_p$. So, it is clear that even for P as small as three or four, the effort to characterize such a system can be prohibitive.

The representation is, however, still useful as a basis for the discussion of the nonlinear behavior of photoemitters. For example, if a photoemitter can be described by (A-1) with P=2 for a restricted domain of input signals, $J(t)=J_o + J'(t)$, where $J'(t)$ is a small modulation on a bias input J_o, then the output signal will be

$$L[p, q; J(t'), t' \leq t] = L_1(t, p, q) + L_2(t, p, q) \tag{A-3}$$

where

$$L_1(t, p, q) = J_o \int_0^\infty dt_1 \, h_1(t_1, p, q) + \int_0^\infty dt_1 \, h_1(t_1, p, q)\, J'(t-t_1) \tag{A-4}$$

$$L_2(t, p, q) = J_o^2 \int_0^\infty dt_1 \int_0^\infty dt_2 \, h_2(t_1, t_2, p, q)$$

$$+ 2\, J_o \int_0^\infty dt_1 \int_0^\infty dt_2 \, h_2(t_1, t_2, p, q)\, J'(t-t_1)$$

$$+ \int_0^\infty dt_1 \int_0^\infty dt_2 \, h_2(t_1, t_2, p, q)\, J'(t-t_1)\, J'(t-t_2) \tag{A-5}$$

For such a photoemitter the small-signal impulse response as obtained from the time derivative of the response to a small step, $J'(t) = a\, U(t)$, will be

$$h_e(t, p, q) = h_1(t, p, q) + 2 J_o \int_0^\infty dt_2\, h_2(t, t_2, p, q)$$

$$+ 2a \int_0^t dt_2\, h_2(t, t_2, p, q) \qquad \text{(A-6)}$$

While, the small-signal frequency response as obtained from the fundamental response to a small sinusoid, $J'(t) = a \sin \omega t$, will be

$$H_e(\omega, p, q) = H_1(\omega, p, q) + 2 J_o H_2(\omega, o, p, q) \qquad \text{(A-7)}$$

where $H_1(\omega_1, p, q)$ and $H_2(\omega_1, \omega_2, p, q)$ are the one- and two-dimensional Fourier transforms of the first- and second-order Volterra kernels, respectively.

The effective small-signal impulse response (A-6) and the effective small-signal frequency response (A-7) are not Fourier transform pairs as they would be for a linear photoemitter. The third term on the right in (A-6), which depends on the step amplitude, has no counterpart in (A-7) since the response at twice the applied frequency is not used in the determination of $H_e(\omega)$. Neither one of these measurements, nor both taken together, serves to characterize a photoemitter even as simple as a second-order Volterra polynomial.

A measurement program that utilizes small-signal step response and yields a complete small-signal characterization of this second-order Volterra system would involve the measurement of the response of the system to the step modulation

$$J'(t) = a_1 U(t-\tau_1) + a_2 U(t-\tau_2) \qquad \text{(A-8)}$$

where τ_1 and τ_2 are the application times of the two steps. It would be required to measure the output as a function of observation time t for a set of values of step separation $\tau_1 - \tau_2$. The numerical differentiation of these data to obtain the second partial derivative of the output with respect to τ_1 and τ_2 would then yield

$$\frac{d^2 L}{d\tau_1 d\tau_2} = 2a_1 a_2 h_2(t-\tau_1, t-\tau_2, p, q) \qquad \text{(A-9)}$$

where only the third term in (A-5) contributes. After having found $h_2(t_1, t_2)$ by this means, $h_1(t_1, p, q)$ would be obtained from (A-6) by subtraction of the terms involving the second-order kernel.

The data acquisition and subsequent calculations involved in such a large program would require sophisticated equipment. Furthermore, the usefulness of the resulting Volterra kernels as engineering parameters has not yet been widely accepted. Therefore, the complete characterization of the nonlinearity of photoemitters remains unattained.

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